NSF/CEE-82098

PB83-186858

ALTERNATIVE METHODS FOR HAZARD REDUCTION IN UNREINFORCED MASONRY BUILDINGS

Final Report
Grant No. CEE-8113750

Michael Durkin
Principal Investigator

Michael E. Durkin and Associates
22955 Leonora Drive
Woodland Hills, CA 91364

A Study For The National Science Foundation

December 1982

68-7

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. NSF/CEE-82098	2.	3. Recipient's Accession No. PB83 186858

4. Title and Subtitle
Alternative Methods for Hazard Reduction in Unreinforced Masonry Buildings, 1982 Final Report

5. Report Date
December 1982

6.

7. Author(s)
M.E. Durkin

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Michael E. Durkin and Associates
22955 Leonora Drive
Woodland Hills, CA 91364

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C) CEE8113750
(G)

12. Sponsoring Organization Name and Address
Directorate for Engineering (ENG)
National Science Foundation
1800 G Street, N.W.
Washington, DC 20550

13. Type of Report & Period Covered
Final

14.

15. Supplementary Notes
Submitted by: Communications Program (OPRM)
National Science Foundation
Washington, DC 20550

16. Abstract (Limit: 200 words)

This report concerns the development of alternative hazard reduction strategies for unreinforced masonry buildings. The major characteristics and evolutionary trends of different types of unreinforced masonry buildings in different urban contexts are summarized. Major damage patterns from past U.S. earthquakes are identified, as well as factors such as configuration, use, location, and construction technology which might affect the seismic performance of different subcategories of unreinforced masonry buildings. A mix of structural, non-structural, and operational earthquake loss reduction strategies appropriate to building characteristics and occupant resources is recommended.

17. Document Analysis a. Descriptors

Earthquakes	Buildings	Architecture
Hazards	Construction	Masonry
Damage	California	Dynamic structural analysis

b. Identifiers/Open-Ended Terms

Ground motion M.E. Durkin, /PI

c. COSATI Field/Group

18. Availability Statement NTIS	19. Security Class (This Report)	21. No. of Pages
	20. Security Class (This Page)	22. Price

(See ANSI-Z39.18) *See Instructions on Reverse* OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)
Department of Commerce

TABLE OF CONTENTS

ABSTRACT

Unreinforced masonry buildings have long been identified as particularly hazardous in earthquakes. However, traditional methods of addressing this problem have proven too costly and difficult to implement.

This is the first in a series of reports dealing with the development of alternative hazard reduction strategies for this building type. This report provides a summary of the major characteristics and evolutionary trends of different types of unreinforced masonry buildings in different urban contexts. It identifies major damage patterns from past U.S. earthquakes, and factors such as configuration, use, location and construction technology which might affect the seismic performance of different subcategories of unreinforced masonry buildings.

The ultimate goal of this research is the development of a methodology to assist buildings owners and occupants to select workable and cost effective hazard reduction solutions for specific unreinforced masonry buildings.

INTRODUCTION

Background

Unreinforced masonry buildings (masonry buildings constructed prior to 1933) have long been considered by structural engineers the most hazardous buildings in earthquakes. Indeed, experience in past United States earthquakes has shown that, as a class, these buildings have performed poorly compared to other types of buildings such as wood frame construction. Since unreinforced masonry buildings still exist today in large numbers in most U.S. communities, they are believed to constitute a serious threat to lives and property. It is, therefore, the considered opinion among earthquake engineering experts that these buildings should either be structurally upgraded to an acceptable level of seismic resistance, or demolished.

These two approaches, the strengthening or demolition of individual buildings, are the two major ways adopted to solve this problem. Typically these approaches have been implemented through public policy either covertly or overtly. For example, most local buildings codes state that a renovation which exceeds 50% of the valuation of the building requires compliance with current codes. A more direct approach has been the implementation of hazardous building ordinances targeting unreinforced masonry buildings. Usually these

ordinances were enacted after an earthquake already had occurred, were difficult to implement, and generated much public controversy; furthermore, they remain largely untested in effectiveness.

At present, hazardous building ordinances and code enforcement touch only a small percentage of the total number of unreinforced masonry buildings that exist in California and other seismically active areas in the U.S.

To further compound matters, by virtue of their age and location, unreinforced masonry buildings in most urban areas in the West are the habitat of marginal businesses and socially and economically disadvantaged residents. In addition, this building type comprises the bulk of the central business district of most small towns. In many cases, the cost of seismically upgrading these buildings is not economically justified. Moreover, demolition would displace low income renters and businesses from their only affordable shelter.

In light of the limited effects and controversial nature of the ordinances, we will clearly continue to have with us, for the forseeable future, a huge inventory of these pre 1933 buildings. Therefore, in order to reduce the earthquake danger to occupants and to the general public posed by

these buildings, as well as economic loss to building owners, it is appropriate to investigate other approaches to this problem.

Objectives

The first in a series of reports, this project will provide the beginning investigation of those factors impacting on damage to unreinforced masonry buildings. It will provide historical background necessary for the development of alternate approaches to the problem.

alternative hazard reduction approaches

These alternative approaches are based on planning, architectural, functional, non-structural and operational aspects of earthquake hazard reduction in existing unreinforced masonry buildings. A few examples will illustrate each aspect.

Planning:

The density of urban development and the way in which unreinforced masonry buildings are located in relation to streets, alleys, and other buildings, will affect their potential hazard. A linear commercial strip of single story masonry buildings is likely to perform differently than a group of multi-story masonry buildings scattered in a central business district in an earthquake. Each type has different implications.

Architectural:

Recent studies in architectural configuration and materials have shown that these factors influence the performance of buildings in earthquakes (1). The performance of an unreinforced masonry apartment building, with closely spaced load bearing walls in which the stresses on the masonry will be very low, will be far better than an unreinforced masonry loft structure with wide span wood floors poorly connected to the exterior walls.

Functional:

Gross definition of building function gives little recognition of occupant density and duration of occupancy, and the nature of the population, as a factor in earthquake hazard. Differing hazard reduction methods will be appropriate for the almost unoccupied storage warehouse, for the densely occupied clothing manufacturing shop, and for a disco. Little attention has so far been paid to methods which focus on protecting occupants, rather than the building. It may be much more economical to reinforce a work bench, and train workers in using it as a shelter, then reinforcing an entire industrial building.

Non-Structural:

Experience from past earthquakes has illustrated that in small to moderate sized earthquakes non-structural damage far exceeds structural damage. Non-structural elements can also result in injury to occupants and costly disruption of services, which, in the case of buildings such as fire stations or hospitals, may in itself be life threatening.

Operational:

This category refers to those actions that building owners, organizational tenants and occupants can take prior to, during and after an earthquake to lessen damage and ensure survival. Experience has

shown that hazard is significantly reduced when occupants have frequently participated in exercises directed towards emergency situations.

unreinforced masonry building typology

Another major topic of this report is the initial categorization of unreinforced masonry buildings along lines that are relevant to the seismic safety problem.

Current regulatory approaches to the problem tend to look only at engineering solutions, and attempt to impose a common standard of renovation on a group of buildings whose construction, architecture, occupancy and organization types in fact incorporate wide variation. Some unreinforced masonry buildings, because of their architectural configuration, may be much safer than others; some, because of their occupancy, may represent much less hazard to life.

To make hazard reduction achievable, it is necessary to categorize the great volume of these buildings to reflect their significant characteristics. Experience has demonstrated that the above factors help determine the real hazards presented by unreinforced masonry buildings. Since building owners and occupants have limited resources for earthquake hazard reduction, an approach based on a combination of these techniques, tailored to specific sub-classes of buildings, is more likely to be acceptable and to be implemented, whether through voluntary action or by regulation.

Place of this Report in Overall Research Objectives

The overall goal of this research program is the development of a methodology for assessing an unreinforced masonry building. This assessment will include recommending a mix of structural, non-structural and operational earthquake loss reduction strategies appropriate to building characteristics and occupant resources.

The objectives of Phase I are more modest. Phase I is conceived as an initial fact finding study necessary for designing and producing this loss reduction methodology. Although numerous decision-making heuristics are readily available, and easily adaptable to hazard reduction, they lack the necessary data. Our main task becomes discovering the relevant data that already exists, or could be found, to provide an empirical basis for decision-making. To accomplish this, the Phase I research plan is designed to provide preliminary answers to the following questions:

a) What are the types and locations of unreinforced masonry buildings that make up the inventory of these buildings in the U.S. Southwest? How have unreinforced masonry buildings evolved?

b) What are the patterns of earthquake damage common to different types of unreinforced masonry buildings?

c) What are the threats to life safety posed by these damage patterns?

d) What lines of inquiry seem most promising for subsequent, more concerted research efforts in this area?

Each of these areas is useful in understanding the nature and extent of this problem and in formulating potential solutions.

For example, knowing where unreinforced masonry buildings are likely to be found in a given community is vital in designing effective earthquake response plans. Knowledge of how different types of unreinforced masonry are likely to be damaged is essential in developing appropriate non-structural and structural damage control strategies tailored to specific building types. Similarly, information on the implications of different damage patterns for subsequent injury and economic disruption is useful in the formulation of realistic occupant response practices and may serve as an incentive for preventative action.

PRELIMINARY FINDINGS AND NEEDED RESEARCH

Findings

1. Despite extensive demolition, unreinforced masonry buildings remain very prevalent in larger cities throughout the west.

2. In smaller communities the number of unreinforced masonry buildings has remained relatively constant over the years.

3. In small cities, unreinforced masonry buildings frequently comprise the bulk of the central business district. As such, these buildings constitute an important component of the building inventory and play a vital role in the economic life of the community.

4. Unreinforced masonry buildings have traditionally experienced use downgrading which lessened their potential as an earthquake hazard. However, this trend may be changing in light of rising construction costs and increasing interest in urban preservation.

5. Due to distinct programmatic and structural characteristics, unreinforced masonry buildings lend themselves to

classification and study along dimensions relevant to the development of earthquake hazard reduction strategies.

6. Unreinforced masonry buildings have exhibited high variability in earthquake resistance. Factors such as site characteristics, mortar strength, proper wall anchors and quality of workmanship appear to influence seismic performance.

7. The effects of age (e.g. deterioration of lime mortar) on the seismic performance of these buildings is not known.

8. There is some evidence to suggest that specific types of unreinforced masonry buildings experience less damage than others. Tentative factors appear to be structure, configuration and relationship of buildings to each other.

9. There have been relatively few instances of the complete collapse of unreinforced masonry buildings in past U.S. earthquakes. However, the failure of parapets, ornamentation and the partial collapse of walls is very common.

10. Although the majority of injuries and fatalities in past U.S. earthquakes have occurred outside rather than inside unreinforced masonry buildings (due largely to the tendency of parapets and walls to collapse outward), little is known about the role that occupant behavior plays in injury avoidance.

Research Needs

This study provides an initial hypothetical basis for decisionmaking concerning appropriate hazard reduction strategies; but we need a more systematic and comprehensive application, to different urban contexts, of the research procedures developed here if we are to have a reliable empirical basis for informed action. This approach should include the following studies:

1. In-depth studies of trends in renovation, demolition and replacement of unreinforced masonry buildings in a variety of urban contexts are needed. Of special interest are areas where vacant buildings are being utilized for unanticipated purposes (e.g. artists' lofts).

2. The role of unreinforced masonry buildings in the economy of small cities requires further investigation. The short and long term economic disruption resulting

from damage to this building type, in past U.S. earthquakes, should also be assessed.

3. An epidemiological study of damage to unreinforced masonry buildings in past U.S. earthquakes should be undertaken to establish more reliable association between specific types of building damage and factors such as configuration.

4. A study of how people in and around unreinforced masonry buildings in past U.S. earthquakes were injured and avoided injury would provide invaluable data for basing occupant response recommendations.

KEY CHARACTERISTICS AND EVOLUTION OF UNREINFORCED MASONRY BUILDINGS IN THE SOUTHWEST

> Earthquakes are not only common, they are sometimes threatening in their violence; the fear of them grows yearly on a resident; he begins with indifference, ends in shear panic; and no one feels safe in any but a wooden house. Hence it comes that, in that rainless clime, the whole city is built of timber--a woodyard of unusual extent and complication; that fires spring up readily, and served by the unwearying trade wind, swiftly spread . . .
>
> Robert Louis Stevenson (2)

In describing a visit to San Francisco before the turn of the century, Stevenson puts his finger on the two hazards most influential in setting the building practices of that city and the rest of California--earthquake and fire. Although, the threat of earthquakes seems to be a key California design determinant responsible for the predominance of single family wood frame housing in residential areas, the fear of fire appears to underlie the predominant use of masonry in the construction of commercial, institutional and industrial buildings.

This section describes the evolution of this building type in California cities, as well as architectural and engineering characteristics of these buildings relevant to this study. In so doing it sets the stage for the subsequent discussion

of some of the major hazards posed by this building type and appropriate methods for earthquake hazard reduction.

Method

In order to study the evolution of unreinforced masonry buildings, four sites in Southern California were selected for analysis. Since we were interested in investigating a range of urban contexts and unreinforced masonry buildings, the following types of settings were chosen:

a) a small town serving an agricultural region

b) a small town which once served an agricultural region but which had been surrounded by suburban development

c) an industrial area serving a major city

d) part of the downtown of a major Southern California city

This analysis consisted mainly of the review of Sanborne maps and other planning data for each of these locations. The Sanborne maps, originally constructed for fire rating purposes and covering the period of the late eighteen hundreds to the mid-nineteen fifties, provided periodic

cross-sectional records of location, use and structural features of all unreinforced masonry buildings in each site. In addition, other documentation provided accounts of key architectural and structural features of these buildings. A general summary of results of this analysis follows.

Locational Patterns

The unreinforced masonry building began to proliferate in California cities around the turn of the century. The number and distribution of these buildings corresponded closely with the rapid growth and development of these cities between 1900 and 1930.

In 1967, it was estimated that as many as 200,000 of these buildings still existed in seismic zone 3 (3).

In large cities such as Los Angeles, these buildings served commercial, industrial and multi-family residential functions. Characteristically, unreinforced masonry buildings of three and four stories could be found clustered in the downtown core areas. In industrial areas, these building grew up next to railroad depots and became warehouses and manufacturing facilities. They tended to be one and two stories in height. Sometimes several individual buildings were pieced together, over time, into large industrial complexes.

In smaller cities, the pattern was somewhat different. Typically, these smaller towns grew up around a transport node such as a rail line. They served as centers of commerce for extensive agricultural surrounds. In this case, one and two story masonry buildings usually formed a central spine along the main street of the town. Subsequently, they grew outward from this spine and filled in an area that became the central business district. Consequently, central business districts throughout the Southwest are comprised mainly of unreinforced masonry buildings.

In both large and small cities, schools and churches built during this period were also primarily of unreinforced masonry construction. However, these buildings were located mainly in residential areas, away from the central business district.

Architecture

Programmatically, unreinforced masonry buildings utilized for commercial purposes had ground floors dedicated to stores, lobbies, banks, restaurants and other commercial establishments. In these buildings, offices or residential rooms occupied the upper levels. Unreinforced masonry apartment buildings, on the other hand, tended to be subdivided into small spaces on all levels. Buildings designed for manufacturing, warehousing and the retail sale of larger

items (e.g. automobiles) usually required large open areas on all levels. Schools consisted of a combination medium-sized classroom spaces and large assembly and recreation areas. Churches also consisted of large assembly areas.

The exterior configuration of most individual commercial buildings was rectangular in plan with a narrow exposure to street front and alleys as dictated by local subdivision ordinances. Industrial facilities tended to be more square in plan. However, the plan configuration of multiples of these buildings was linear in nature with blocks of unreinforced masonry buildings butted up against each other and separated by party walls. In small towns, the commercial strip configuration consisted of one and two story structures. In large cities, such as downtown Los Angeles, block after block of four story buildings could be found. Industrial buildings grow incrementally with the addition of new structures, not necessarily of unreinforced masonry. In structures used for residential and office functions, the configuration above the ground floor varied to permit the entry of light. Most commercial buildings had large street front openings.

Practically all unreinforced masonry buildings had some form of exterior architectural ornamentation including cornices,

molding and statues. A key architectural element was the parapet or firewall which was a wall of brick projecting to a height of two to four feet above the roof and was built on top of the party walls which separated adjacent buildings. The parapet had the utilitarian function of affording shelter to firemen while directing hoses on adjacent buildings (4). Frequently, the parapet also served to increase the perceived height of the street facade of the building.

The interior configuration of unreinforced masonry commercial buildings consisted mainly of a large open area adjacent to the street entrance with smaller spaces for offices and storage toward the alley. On the floors above, the spatial organization usually consisted of small spaces along a double loaded corridor. Vertical spatial elements included stairways, fire stairs and elevators. Lath and plaster was frequently used as a finish material for walls and ceilings, however, the use of hollow masonry tiles was also quite common. Industrial structures differed considerably from commercial in their horizontal organization and their lack of small interior spaces. However, most manufacturing and warehousing buildings had some smaller interior spaces which are offices, storage areas and restrooms.

Engineering

The typical unreinforced masonry building consisted of load bearing walls composed of three wythes of brick; the middle wythe often was made up of pieces of broken brick. A weak lime mortar was standard for earlier buildings; however, mortar strength periodically increased. For example, the City of Long Beach, between 1910 and 1930, had three separate standards for mortar (5).

The floors and roof of unreinforced masonry buildings was essentially of wood frame construction with wooden joists or light wood trusses commonly used in residential and commercial buildings. In industrial buildings, where longer spans were required, deep wooden trusses supported by pilisters were often utilized. Many interior walls, which were non-load bearing, were of wood frame construction.

Evolution

Over the years, both the inventory of unreinforced masonry buildings and the use to which these buildings are put has changed considerably. As Southwestern cities passed from central city development to post war suburban expansion then back to downtown revitalization during the 60's and 70's, the nature of unreinforced masonry buildings, the oldest component of the building element, changed accordingly. For example, the analysis of Sanborne maps showed that in

parts of downtown Los Angeles, millions of square feet of unreinforced masonry building was demolished to make room for parking lots considered at that time to be one of the few profitable uses of downtown real estate. During the next two decades millions of additional square feet of these buildings were demolished to make way for new construction stimulated by urban renewal and renewed private sector investment. In small cities the size of the building inventory remained pretty much the same. As downtowns lost business to the new suburban shopping centers, unreinforced masonry buildings remained standing but were often vacant above the first floor. The function of these buildings was frequently downgraded. For example, as businesses constructed more modern manufacturing plants, the unreinforced masonry buildings, which once served this purpose, were converted to warehouses. In addition, regulatory programs, such as implementation of the Field Act which removed or strengthened many pre 1933 school buildings, have also modified the present inventory.

However, the increasing interest in urban preservation coupled with the increasing cost of new construction has, during the past decade, increased the economic attractiveness and consequent utilization of unreinforced masonry buildings, although the extent of this increase is difficult to measure.

DAMAGE TO UNREINFORCED MASONRY BUILDINGS

> Masonry buildings were the principal sufferers and their failure occasioned the principal loss of life. (Conclusion of Coroner's Jury Inquest: 1933 Long Beach Earthquake) (6)

> The photographer commonly presents only views of the worst damage that can be found. The general result is an exaggeration of the proportion of loss to sound value for the entire badly shaken district. (J. R. Freeman: Earthquake Damage and Earthquake Insurance) (4)

Background

The unreinforced masonry building is often cited as the building type most prone to damage in earthquakes. The high relative damage sustained, during past earthquakes, by this type of construction has been attested to over the years by numerous investigative commissions and earthquake experts (7) (4) (8). However, this general conclusion needs further refinement, since unreinforced masonry buildings have, for reasons explainable and some still unexplainable, exhibited a variability in their performance in past earthquakes. For example, the astonishing observation that a particular unreinforced masonry building has suffered serious damage while an apparently similar masonry building located next door suffers little damage is frequently found in earthquake commentary (8).

This section of the report will begin to put into perspective the relative vulnerability of unreinforced masonry buildings to damage during earthquakes. The discussion will include a review of the conclusions of past investigators which have been put forth to explain aspects of this variability. We will also present data on the types of damage which most frequently affect unreinforced masonry buildings, as well as some speculation on some critical design and planning variables which may contribute relative damage among this building type. We hope thus to identify the more important variables influencing the kind of damage a particular unreinforced masonry building is likely to suffer.

Method

The material in this section results from a review of available damage and loss data from the following U.S. earthquakes:

a) San Francisco, 1906
b) Santa Barbara, 1925
c) Long Beach, 1933
d) Imperial Valley, 1940
e) San Fernando, 1971 (City of San Fernando)

Available time permitted only a cursory review of damage data from Bakersfield, 1952, and El Centro, 1979.

Damage In Past U.S. Earthquakes

The propensity of unreinforced masonry buildings to suffer relatively more damage than other building types is well documented in the subjective and expert reports of past earthquakes. More statistical support for this argument comes from quantitatively based comparative analyses of damage in the cities of Long Beach during the 1933 earthquake (5) and San Fernando in the 1971 earthquake (9).

However, this conclusion should be viewed in light of two other findings from studies of past earthquakes. That the overall incidence of damage to any building type in a given earthquake is relatively small, is the first finding. That only a small proportion of unreinforced masonry buildings actually undergo complete collapse or suffer extensive damage requiring demolition is the second.

In his classic essay, Earthquake Damage and Earthquake Insurance, written in 1932, Freeman notes that records of past earthquakes indicate "that the ratio of loss to sound value in a great earthquake within any one municipality as a whole seldom exceeds five to ten percent" (4). As evidence, he cites San Francisco, 1906, Tokyo, 1923, and Brawley, 1915, where the damage ratio was approximately 5%. An exception is Santa Barbara, 1925, where damage to the city's

central business district comprised mainly of unreinforced masonry buildings was about 50%. However, this earthquake was an unlikely example of a localized shock, originating practically underneath the downtown area (10).

The small proportion of the "population at risk" of unreinforced masonry buildings seriously damaged is also documented in other past earthquake reports. For example, only about twelve cases of complete collapse in the 1906 San Francisco earthquake have been confirmed (11). The Coroner's Inquest into the Long Beach Earthquake concluded that ". . . fully 78% of the buildings in the affected area suffered only inconsiderable damage . . . ." (6). In fact, of 1623 unreinforced masonry buildings surveyed by the Long Beach Building Department, only about 5% were considered damaged to the extent that made repair impracticable (5).

Although, at a gross level, it appears that the relative risk of severe damage to any one building in a given earthquake is low, it is also evident that even moderate damage can pose risks to life and property. Therefore, the damage data was further analyzed to document the contributing factors to damage in unreinforced masonry construction. These are:

a) site characteristics/foundations
b) poor mortar

c) inadequate wall anchors

d) poor workmanship

e) configuration

Site Characteristics/Foundations

Foundation conditions can vary greatly within a short distance. One lot may be on solid rock, the next on alluvium. Since many urban areas where unreinforced masonry buildings predominate were established near the coast or in valleys, on natural sediment or artificial fill, the chance of damage of buildings in these areas is greater than to similar buildings on solid rock. "Only large earthquakes reach damaging intensity on solid rock; but many moderate or even small earthquakes cause damage, more or less widespread, to weak structures on alluvium," noted Charles Richter (8). Poor soil conditions was cited as contributing to the extensive damage to unreinforced masonry buildings in the 1925 Santa Barbara earthquake (12).

The seismic stability of unreinforced masonry buildings, as a type, is further threatened because many of these buildings, due to absence of code requirement and/or programmatic need for a basement (13), fail to have adequate foundations. In his account of building damage in the San Francisco Earthquake, Himmelwright observed that, "whenever foundations were

displaced, they were either poorly designed or were not of sufficient depth to reach stable material" (7).

The lack of sufficient foundations for an unreinforced masonry building also increases the chances that the building will settle during or after an earthquake.

Poor Mortar

Poor mortar is frequently cited by engineers as the principal cause of the failure of unreinforced masonry buildings in earthquakes. That most early masonry construction utilized a weak lime mortar made from readily available materials was mentioned in the previous section. It was not until around 1930 that enlightened municipalities, influenced largely by the Uniform Building Code of that year, began to require the use of a larger percentage of cement in mortar.

After the 1933 earthquake, the Long Beach Building Department compared damage to masonry buildings constructed prior to 1930 with damage to those unreinforced masonry buildings constructed afterwards and having theoretically used the stronger mortar. The post 1930 unreinforced masonry buildings were shown to have sustained relatively less damage. For example, only 1% of the post 1930 buildings as opposed to 5% of the pre 1930 buildings were damaged beyond repair, while only 3% of post 1930 structures, as opposed to 17% of pre

1930 structures sustained significant damage (5). However, there were only 77 post 1930 buildings as compared with over 1600 pre 1930 unreinforced masonry buildings in the survey.

The tentative conclusion here is that unreinforced masonry buildings, constructed more recently, have a better chance of having stronger mortar, and therefore exhibit superior performance.

Inadequate Wall Anchors

Perhaps the major deficiency of unreinforced masonry buildings is that they were designed with no allowance for withstanding the lateral forces caused by earthquakes. In particular, walls were not adequately anchored to floor and roof framing or to each other. The SEASC Committee investigating the Long Beach Earthquake concluded that even when joist anchors were installed, according to the building codes of the time, they either pulled out of the wall or they broke. A more efficient type of joist connection was found to be steel angles bolted to a concrete bond beam (13). The effectiveness of anchoring floors and roofs to walls as a means of increasing the survivability of unreinforced masonry buildings has been marked by past controversy. For example, at a 1925 meeting of the San Francisco Section of the American Society of Civil Engineers to discuss damage in the Santa Barbara Earthquake, J. D. Galloway speculated that in the case of

the California Hotel, adequate wall anchoring would have resulted in complete collapse of this building instead of failure to portion of the exterior wall (14). However, this theory does not seem to be supported by other earthquake engineering experts of this period (7).

Poor Workmanship

Most unreinforced masonry buildings were constructed during periods of rapid economic growth and in the absence of effective building regulations. In addition, most of these buildings were built for speculative purposes with the emphasis on minimizing construction costs. As a result, the level of construction quality in many of these buildings was grossly substandard. For example, in his testimony to the Long Beach Coroner's Inquest, James C. Bair recounted inspecting a damaged building and finding that the anchors not only had not been attached to the roof joist but had been bent out of the way during construction (6). Waile's and Horner's report provides a good description of improvements in workmanship and building inspection in Long Beach between 1913 and 1930 (5).

Gross Building Damage

That not all unreinforced masonry buildings are strong candidates for collapse in earthquakes appears to have been

the consensus of many of the early observers of earthquake damage. "Well-built structures of wood or brick or of squared stone laid up in strong mortar, have generally withstood earthquake shock," observed Freeman (4). "Well constructed buildings were undamaged," reported W. H. Homes from the scene of the 1940 Imperial Valley Earthquake (15). "Damage was mostly confined to those (masonry buildings) built with poor quality of lime mortar, inadequate bonding and anchoring, or of inferior workmanship, and built to designs that took no account of horizontal forces," concluded the Long Beach Coroner's Jury (6). "In all cases where a good quality of lime mortar or Portland cement was used, and where the workmanship was fairly good, much less damage was noted, and the results were always vastly superior to the average work," stated Himmelwright after studying earthquake damage in San Francisco. He went on to say that "walls tied together with rods or straps always showed better results than those without such ties" (7).

However, Richter adds a qualification to the previous statements by suggesting that the term "well-built does not describe the obsolete, jerry-built structures in many business areas . . . ." (8).

Differences Among Building Types

We were interested in more than identifying the major factors which contribute to the poor performance of unreinforced

masonry buildings in earthquakes, at a gross level, as well as the major types of building failure. We wanted to see if there was any evidence to suggest that certain building types might perform differently than others in earthquakes.

Two such attempts occurred after the 1933 Long Beach Earthquake. In one, the Long Beach Building Department categorized damage to post 1930 unreinforced masonry buildings by building type. Although residential and commercial buildings were not damaged as extensively as industrial buildings and public garages, the quantity of each building type represented in this study was so small (e.g. only three warehouses) as to make comparison difficult (5). It would have been more useful to compare damage to a breakdown of the pre 1933 buildings in Long Beach.

The second attempt to find an association between damage and building type involved an assessment of damage to unreinforced masonry buildings in Compton, California following the 1933 earthquake by Professor Martel of Cal Tech (16). Martel's comparison of damage to commercial structures versus damage to residential buildings revealed that 73% of the commercial structures surveyed had sustained damage greater than 50% of their value, while only 10% of the residential structures had suffered the same fate. However, this finding is compromised once again by the small number of residential

buildings involved (21 residential buildings) and because it remains unclear which building types are included in each category (e.g. are apartment hotels considered to be commercial or residential).

Building Configuration

We were also interested in exploring the impact, if any, of architectural configuration on the seismic performance of unreinforced masonry buildings.

Height

One such aspect is building height. For example, after viewing damage in the 1925 Santa Barbara earthquake, Col. Clarke S. Smith concluded, "where the height of the (unreinforced masonry) structure is above two stories, more massive construction . . . is not sufficient to withstand the shock" (17). Similar comments have been made by other observers of past earthquake damage.

In reviewing newspaper accounts of damage to the city of Brawley in the 1940 Imperial Valley Earthquake, it is striking that five of the ten buildings reported to be most seriously damaged were hotels of two stories or more (15). In addition, we found that six of the nine buildings in downtown San Fernando, which were actually demolished, were two stories high (one building was three stories tall).

Plan Configuration

The L-shaped building is one configuration that has been marked as particularly vulnerable in earthquakes (1). The failure in the Santa Barbara Earthquake of the central portion of the L-shaped San Marcos Building, due to intensified forces converging at the juncture of the two parts of the building, has been described in several reports (4) (12). Although this building had a reinforced concrete structural system, its seismic performance seems applicable to unreinforced masonry buildings of this configuration. In fact, our review of damage in the City of San Fernando revealed that three of the six two story buildings demolished shared the L-shaped configuration.

Aggregate Configurations

Although engineers tend to treat unreinforced masonry structures as individual buildings, these buildings often are found in groups. As such, the aggregate configuration of these buildings seems to have the potential for contributing to the performance of individual buildings in each group. For example, after reviewing 1971 earthquake damage Abel noted that "in some cases, it was apparent that an adjacent building shared the load and reduced the damage" (18). Other reports from downtown Los Angeles cite damage caused by buildings knocking against each other. In reviewing damage in the City

of San Fernando, it was apparent that, in several cases, damages to a building resulted from the partial failure of an adjacent building (e.g. a collapsed parapet falling through the roof of a nearby structure).

The impact of aggregate configuration on building damage is a largely unexplored area which deserves future systematic study.

Specific Damage Patterns

Although relatively few unreinforced masonry buildings have suffered complete collapse in past U.S. earthquakes, numerous buildings have experienced partial failure. Parapets were perhaps the most frequent example of partial building failure. In accounting for this characteristic behavior during the Long Beach Earthquake, Martel made the following comments:

> I think perhaps one of the contributing reasons for the fall of the fire walls in the stricken area was the placing of flashing in the brick work, which hadn't very much tensile strength anyway, so that given its chance it would fall out rather than in. Of course, the roof itself isn't very rigid and acts, I think, as a battering ram right at that point (6).

Improperly attached exterior ornamentation often became dislodged. Unbraced non-structural elements such as cooling towers often collapsed and fell through roofs. Exterior walls

were frequent casualties, as evidenced by extensive cracking in or partial collapse (usually outward) of one or more of the three brick wythes. In many cases, it was concluded that the combination of wood frame floors, ceilings and non-bearing interior walls provided a structural redundancy which prevented complete building collapse (1).

Damage to the interior of buildings usually consisted of cracked and fallen plaster from ceilings and walls, broken glass, and overturned building contents. Hollow tile walls have performed very poorly.

CASUALTIES IN UNREINFORCED MASONRY BUILDINGS IN PAST U.S. EARTHQUAKES

> Few people have been killed or injured by earthquakes as such. Hundreds of thousands have lost their lives in the collapse of buildings which were so weak that they never would have been erected under any proper system of building . . . Charles Richter (8)

In this century alone, over a million people have been killed or injured in earthquakes worldwide. For example, between 1960 and 1976, 140,000 people perished in major earthquakes throughout the world (19). On July 28, 1976, the Tangshan, China earthquake killed an additional 240,000 people and injured 164,000 more (20). The overwhelming majority of these casualties have occurred in and around unreinforced masonry buildings.

Fortunately, the United States so far has been spared the high mortality rate of other countries. There were 120 fatalities in the 1933 Long Beach Earthquake (6). Only two fatalities and 32 injuries were reported in the 1952 Bakersfield, California Earthquake (21). Of the 130 deaths and 50 injuries attributed to the 1964 Alaska earthquake, most casualties were caused by the ensuing tsunami (22). It is not clear if any of the remaining deaths or injuries occurred in unreinforced masonry buildings. Only one fatality of the 1971 San Fernando

Earthquake occurred in an unreinforced masonry building; however, two other deaths resulted from the collapse of masonry walls (23). It is not clear how many of the 5000 reported injuries were caused by unreinforced masonry buildings. Table A presents a listing of selected U.S. earthquakes prior to 1930 (4).

TABLE A
FATALITIES IN SELECTED U.S. EARTHQUAKES
1930 AND PRIOR

Fatalities	Earthquake	Year
30	San Francisco	1868
30	Owens Valley	1872
100	Charleston	1886
700	San Francisco	1906 (including fire)
10	Calexico-Mexicali	1915
7	Santa Barbara	1925
None	Calexico-Mexicali	1925
None	Whittier	1929
None	Brawley	1930

This good fortune is due primarily to 1) significant differences in construction between unreinforced masonry buildings in the U.S. and that found in most foreign countries, and 2) the fortuitous timing of past U.S. earthquakes.

Differences in Construction Technology

In describing the devastation of earthquakes abroad, Freeman notes that the ". . . losses of many lives in foreign cities have occurred mostly in top heavy structures, having walls

built largely of rounded stone, feebly held together by weak lime-mortar and floors and roofs that are heavy and weakly supported by girders not strongly tied into the supporting walls" (4).

However, as we have seen in the preceding chapter, unreinforced masonry buildings in the U.S., although frequently constructed with a weak mortar, tend to have relatively lightweight wood frame floor and roof structures less prone to internal collapse. Instead, the walls, weak parapets and weakly tied ornamentation such as heavy cornices and veneers of these buildings are more apt to fracture and fall outward, thereby threatening people on the outside. Indeed, the Coroner's Inquest following the 1933 Long Beach Earthquake concluded that the failure of masonry buildings occasioned the principal loss of life (6). In addition, the Joint Technical Committee stated in June of 1933:

> No precise estimate can be made, but it is clear that a very large proportion of the total deaths and injuries resulted from debris falling on people who were in the streets, at the time, or who ran into the streets at the first shock. Much of this debris consisted of bricks from parapet walls; poorly supported cornices contributed to the mass of falling objects; and the front walls of shops toppled off their girder supports and crushed anything beneath (24).

Fortuitous Timing

So far, we have been very lucky with respect to the timing of damaging earthquakes here in the United States. For

example, the 1933 Long Beach Earthquake, which caused extensive damage to unreinforced masonry school buildings in the cities of Compton, Long Beach and Huntington Park, occurred at 5:45 in the afternoon when the schools were mostly empty (5). Only two fatalities occurred in the schools (6).

The 1964 Alaska earthquake, although 8.4 in magnitude, struck a sparsely populated area in the late afternoon of Good Friday, when offices and commercial establishments were closed and many people were driving home in the relative safety of their automobiles (22).

The death toll in the Midnight Mission, the second floor of which partially collapsed during the 1971 San Fernando Earthquake, certainly would have been higher if the event had occurred three hours later when more people were in the building (18).

Occupant Behavior

The appropriate behavior of building occupants is a little understood but essential area in earthquake hazard reduction. Little documentation concerning successful injury avoidance in unreinforced masonry buildings is easily obtainable. However, one such account of a Long Beach fire station occupant illustrates some aspects of the relationship between typical building damage and occupant behavior.

> At the same time, at Central Station, the shocks caused the entire second floor front wall to fall outward, and the rear wall went, too. At that time of day, most of the personnel at this station were on the second floor near the front wall in the recreation room. When the first shocks occurred, there was a mad scramble to get out and away from the building. One man stepped through a window to an outside balcony, only to be carried down with the collapse of the front wall. Other men dropped down the sliding pole to the apparatus floor, most of them diving under apparatus, fearing the second floor would collapse. A lieutenant, instead of availing himself of this protection, dashed out the front door, only to be caught by the falling wall. Both he and the man who stepped through the window were killed (25).

One primary aspect of occupant behavior that emerges from this account is the amount of time available for engaging in protective behavior. The relationship of this factor to different levels of building failure needs more extensive study.

BIBLIOGRAPHY & REFERENCES

1 Arnold, C. and R. Reitherman, *Building Configuration and Seismic Design: The Architecture of Earthquake Resistance* (San Mateo, CA: Building Systems Development) May 1981.

2 Stevenson, R. L., "Pacific Capitals", in J. D. Hart (ed) *From Scotland to Silvarado* (Cambridge, Mass.: The Belknap Press of Harvard University) 1966.

3 Uniform Building Code, 1967 edition.

4 Freeman, J. R., *Earthquake Damage and Earthquake Insurance* (New York: McGraw-Hill Book Company) 1932.

5 Weiles, Jr., C., D., and A. C. Horner, *Survey of Earthquake Damage at Long Beach, California* 1933.

6 Los Angeles County Coroner's Office, *Transcript of Testimony and Verdict of the Coroner's Jury in the Inquest Over Victims of the Earthquake of March 10, 1933*. September 1933.

7 Himmelwright, A.L.A., *The San Francisco Earthquake and Fire: a brief history of the disaster* (New York: The Roebling Construction Company) 1906.

8 Richter, C. F., "Our Earthquake Risk: Facts and Non-Facts, *California Institute of Technology Quarterly*, January 1964.

9 Steinbrugge, Karl V. and E. E. Schader, "Earthquake Damage and Related Statistics" in L. M. Murphy (ed) *San Fernando, California, Earthquake of February 9, 1971* (Washington: N.O.A.A.) 1973.

10 Woods, Harry, O., "The Practical Lesson of the Santa Barbara Earthquake," *Allied Architects Association Bulletin*, August 1, 1925.

11 Nason, R., *Damage in San Francisco, California, caused by the earthquake of 18 April 1906*, United States Geological Survey Open File Report, 1981 reported in Reitherman "Earthquake: What to do and why", California Geology, March 1982.

12 Dewell, Henry, D., "Earthquake Damage to Santa Barbara Buildings," *Engineering News-Record* Vol. 95, No. 2, pp. 68-72, July 9, 1925.

13 Structural Engineers Association of Southern California, The Long Beach Earthquake of 1933, Committee report, (Los Angeles: SEASC) 1933.

14 "Engineers Discuss Earthquake Experiences and Cautions," Engineering News-Record, Vol. 95, No. 7, pp. 271-272, August 13, 1925.

15 Homes, W. H., Report On The Damage Caused By The Earthquake Of May 18, 1940 In Imperial Valley And Vicinity, May 22, 1940, report submitted to Division of Water Resources, State of California.

16 Martel, R. R., "Earthquake damage to Type III buildings in Long Beach, 1933, (in) Earthquake investigations in the western United States, USGS Publication 41-2. (reported in) R. Gulliver and P. Somerfeld, Estimation Of Homeless Caseload For Disaster Assistance Due To An Earthquake, Federal Emergency Management Agency (draft).

17 Smith, C. S., Additional Notes on Santa Barbara Earthquake Effects," Engineering News-Record, Vol. 95, No. 6, pp. 228-230, Aug. 6, 1925.

18 Abel, M. A., "Unreinforced Masonry Buildings," in L. M. Murphy (ed) San Fernando Earthquake of February 9, 1971 (Washington, D. C.: NOAA) 1973.

19 de Villa de Goyet et. al. "Earthquake in Guatemala: Epidemiologic Evaluation of the Relief Effort," Bulletin of the Pan American Health Organization 10(2), 95-109, 1976.

20 Earthquake Engineering Research Institute. The 1976 Tangshen, China Earthquake (Berkeley, CA: EERI) March 1980.

21 Fritz, C. E. and Shirley A. Star, "A Preliminary Report on the Bakersfield California Earthquake, August 1952, In, E. S. Marks and C. E. Fritz (eds) Human Reactions In Disaster Situations (Unpublished Manuscript) National Opinion Research Center, 1954.

22 Lantis, M., "Impact of the Earthquake on Health and Mortality," in The Great Alaska Earthquake of 1964: Human Ecology (Washington, D.C.: National Academy of Sciences) 1970.

23 Los Angeles County Coroner's Office, Deaths Other Than Those Connected With San Fernando Veterans Administration Hospital, 1971.

24 Joint Technical Committee on Earthquake Protection, *Earthquake Hazard and Earthquake Protection*, Los Angeles, California, June, 1933.

25 DuRee, A. C., "Fire Department Operations During The Long Beach Earthquake Of 1933," *Bulletin of the Seismological Society of America*, Vol. 31, No. 1, pp. 9-12, January 1941.